FLOW OF ICE I BY DISLOCATION, GRAIN BOUNDARY SLIDING, AND DIFFUSION PROCESSES.

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Experimentally derived constitutive equations describing the macroscopic flow of ice are essential for extrapolating measurements of rheological behavior from laboratory to planetary conditions. Because ice can flow by a number of micromechanical processes including the motion of dislocations, diffusion of atoms and sliding of grain boundaries, we have undertaken experiments to quantify the creep properties of Ice I over wide ranges of temperature, stress and grain size. Prior to the present investigation, most studies of the rheology of ice were carried out in the dislocation creep regime on samples with relatively large grain sizes ($\gtrsim$ 1 mm).

To determine constitutive equations that accurately describe the creep of ice in the diffusion and grain boundary sliding regimes at the relatively high stresses and strain rates accessible in laboratory experiments, samples were fabricated with grain sizes of 3 to 200 μm by hot-pressing fine-grained powders and exploiting the Ice I to Ice II phase transition (*Goldsby and Kohlstedt*, 1997; *Durham et al.*, 1994). Compressive creep experiments were carried out in a high-resolution one-atmosphere deformation rig (*Mackwell et al.*, 1990; *Goldsby and Kohlstedt*, 1995) at differential stresses between 0.2 and 20 MPa and temperatures between 170 and 268 K; the resulting strain rates were in the range 10^{-8} and 10^{-4} s^{-1}. The experimental results were analyzed in terms of a constitutive equation composed of a combination of power law flow laws of the form

$$\dot{\varepsilon} = A\frac{\sigma^n}{d^p}\exp\left(-\frac{Q}{RT}\right) \qquad (1)$$

where $\dot{\varepsilon}$ is the strain rate, *A* is a materials parameter, σ is the differential stress, *Q* is the activation energy for creep, and *RT* has the usual meaning. Microstructures of deformed and undeformed samples were analyzed using a cryogenic stage in an environmental scanning electron microscope (ESEM); with this ESEM it was possible to obtain high-quality images of the grain structure of our fine-grained samples without coating the surface with an electrically conducting film and without sublimation of the sample as would occur at the higher vacuum needed for a conventional scanning electron microscope.

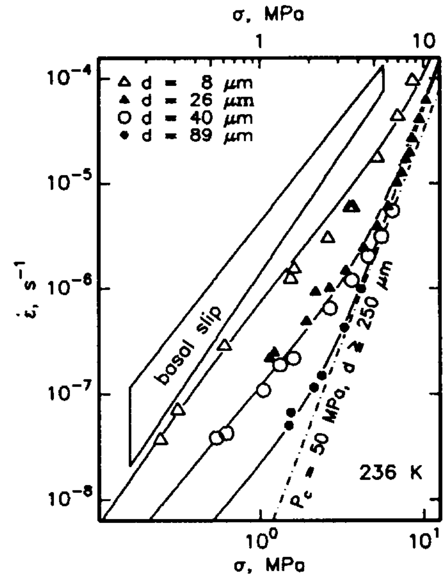

Figure 1: Log-log plot of strain rate versus differential stress for four samples of fine-grained ice deformed in compression at 236 K. Results for slip on the basal plane in single crystals (*Wakahama* 1967; *Ramseier*, 1972; *Homer and Glen*, 1978) and for deformation at high confining pressures on polycrystalline aggregates (*Durham et al.*, 1992) are included for comparison. The solid curved lines are best fits of Eq. 2 for the appropriate grain sizes.

Typical creep data obtained at 236 K for samples with grain sizes of 8, 26, 40 and 89 μm are presented in the log-log plot of strain rate versus stress in Figure 1. At the highest stress levels, the stress exponent *n* approaches 4.5, a value indicative of dislocation creep. As stress is decreased, the stress exponent decreases to ~1.8, a value approaching those predicted by models of grain boundary sliding or diffusion creep; the strain rate is inversely proportional to grain size with p = 1.4. At the lowest stresses, *n* approaches 2.4, a value similar to that reported for easy glide in single crystals of ice.

These observations suggest that at least three creep processes are important in the flow of polycrystalline Ice I. (1) For the highest stresses, our results are in excellent agreement with those of *Durham et al.*

(1992) for dislocation creep. In this high-stress regime, the creep rate is limited by motion of dislocations on one of the hardest slip systems. (2) For intermediate stresses, we argue that the creep rate is limited by dislocation accommodate grain boundary sliding. In this intermediate-stress regime, electron micrographs reveal numerous four-grain junctions identical to those that occur as part of grain switching events during grain boundary sliding (*Ashby and Verrall*, 1973). Published values for grain matrix diffusivities and estimates of grain boundary diffusivities in ice based on published results for a wide range of crystalline materials suggest that diffusion creep (either Nabarro-Herring or Coble creep) is not an important deformation process in ice with a grain size of more than 100 μm under any geologically relevant conditions. (3) For the lowest stresses, the strain rate becomes limited by motion of dislocation on the easy (basal) slip system in ice. In this low-stress regime, grain boundary sliding is also an important deformation mechanism, however, the rate of grain boundary sliding is limited by the motion of dislocations on the easy slip system.

Based on this analysis, the creep data in Figure 1 were fit to the following constitutive equation:

$$\dot{\varepsilon}_{\text{total}} = \left[\frac{1}{\left(\dot{\varepsilon}_{\text{hs}} + \dot{\varepsilon}_{\text{es}}\right)} + \frac{1}{\dot{\varepsilon}_{\text{gbs}}}\right]^{-1} + \left[\frac{1}{\dot{\varepsilon}_{\text{hs}}} + \frac{1}{\dot{\varepsilon}_{\text{es}}}\right]^{-1} \qquad (2)$$

In this equation, the subscripts *hs*, *es* and *gbs* denote the strain rate due to slip on the hard slip system, slip on the easy slip system and grain boundary sliding, respectively. Each of the terms on the left hand side of Eq. 2 has the form of Eq. 1 with values for n and p given above.

To test the applicability of our experimentally derived constitutive equation to flow under geological conditions, we compared the behavior predicted by Eq. 2 with that observed in measurements of the flow behavior of glaciers. In the specific case of Meserve Glacier for which the stress and temperature are well-constrained, a transition with decreasing stress from a regime in which n = 4.5 to a regime in which n = 1.9 at a differential stress of ~0.1 MPa has been reported (*Holdsworth and Bull*, 1968). Furthermore, values for strain rate predicted by Eq. 2 are essentially identical to values obtained from field measurements for this glacier.

We conclude, therefore, that the deformation behavior of Ice I is dominated by dislocation and grain boundary sliding processes and that diffusion creep will not contribute significantly over the full range of planetary conditions. Flow of Ice I is well-described, then, by a combination of power law equations combined in the form of the constitutive equation in Eq. 2. Deformation on the hard slip system is characterized by n = 4.5 and Q = 60 kJmol^{-1}; deformation on the easy slip system is given by n = 2.4 and Q = 60 kJ mol^{-1}; deformation by grain boundary sliding is defined by n = 1.8, p = 1.4 and Q = 49 kJ mol^{-1}. Furthermore, we conclude that the lowest-stress regime identified in our experiments is unlikely to be important at planetary conditions. Hence, superplastic flow -- that is, grain boundary sliding in combination with dislocation motion -- is an important and often dominant mechanism of deformation in icy satellites.

[1] Ashby, M.F. and R.A. Verrall, Diffusion-accommodated flow and superplasticity, *Acat Metal.* 21:149-163, 1973.

[2] Durham, W.B., S.H. Kirby, and L.A. Stern, Effects of dispersed particulates on the rheology of water ice at planetary conditions, *J. Geophys. Res.* 97:20883-20897, 1992.

[3] Durham, W.B., L.A. Stern, and S.H. Kirby, Grain size dependent creep of Ice I at low temperature: Preliminary results, *EOS*, American Geophysical Union, 75:635, 1994.

[4] Goldsby, D.L. and D.L. Kohlstedt, Diffusion creep in ice, in *Rock Mechanics Proceedings of the 35th U.S. Symposium*, eds. J.J.K. Daemen and R.A. Schultz, A.A. Balkema, Rotterdam, pp. 199-206, 1995.

[5] Goldsby, D.L. and D.L. Kohlstedt, Grain boundary sliding in fine-grained Ice I, *Scripta Met.* submitted, 1997.

[6] Holdsworth, G. and C.C. Bull, The flow law of cold ice; investigations on Meserve Glacier, Antarctica, in *International Symposium on Antarctic Glaciological Exploration, Hanover, NH*, eds. A.J. Gow, C.C. Langway, and W.F. Weeks, IAHS Pub. 86, pp. 204-216, 1968.

[7] Mackwell, S.J., D.L. Kohlstedt, and W.B. Durham, High-resolution creep apparatus, in *The Brittle-Ductile Transition in Rocks: The Heard Volume*, eds. A.G. Duba, W.B. Durham,, J.W. Handin, and H.F. Wang, American Geophysical Union, Washington, pp. 235-238, 1990.